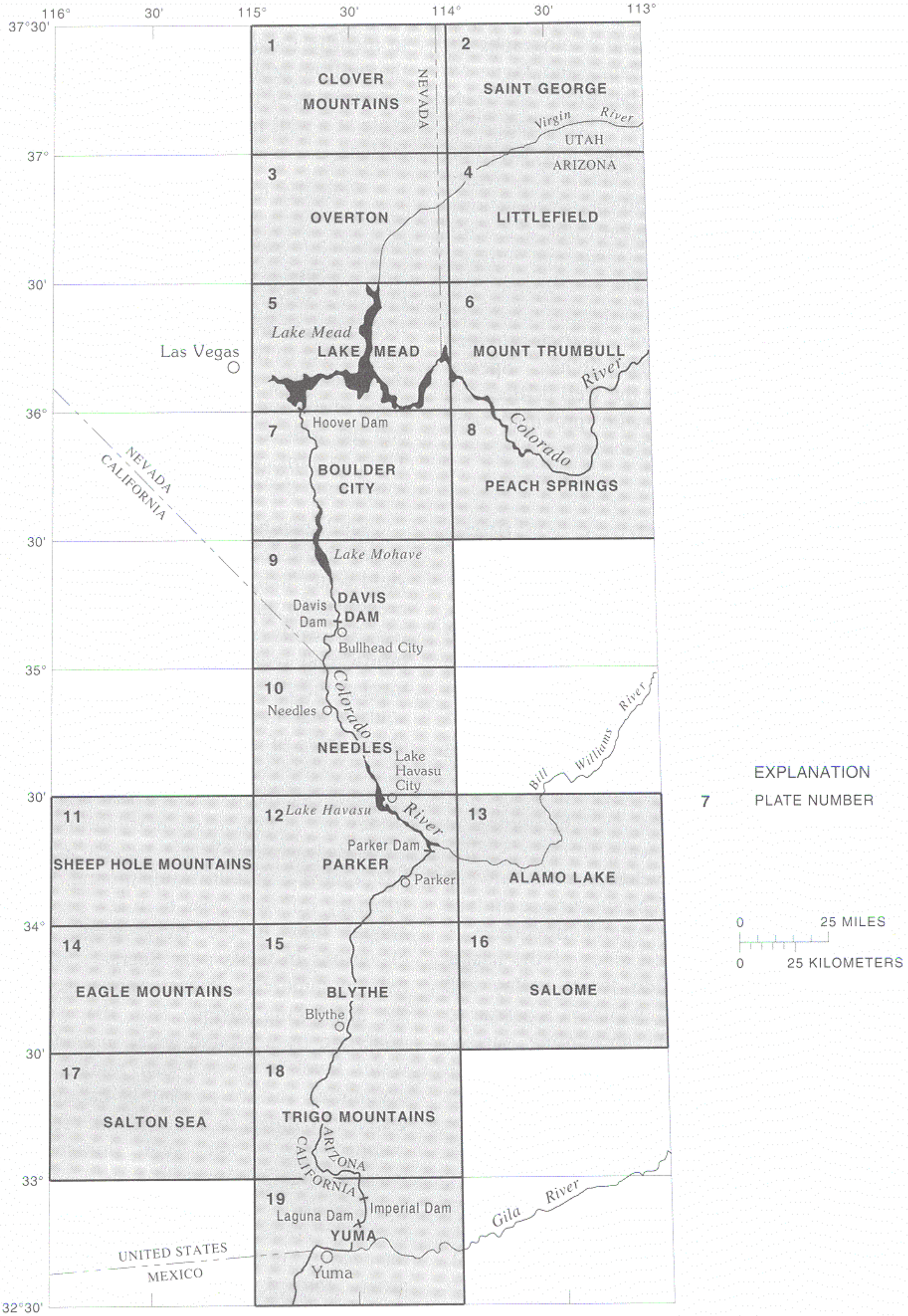


Figure 2. Index to maps of the river aquifer and accounting surface in the lower Colorado River valley, plates 1-19.

provided equipment and aerial photographs for field operations. E.F. Di Sanza and Jayne M. Harkins, Bureau of Reclamation, provided Colorado River profiles below Davis Dam. The Colorado River Indian Tribes and the Fort Mohave Indian Tribe kindly provided hydrologic data and access to their reservations. Irrigation districts, municipal utilities, and water companies provided well records and allowed access to their wells. San Bernardino and Riverside Counties in California provided well logs. Palo Verde Irrigation District provided water-level data for drainage ditches. Special appreciation is extended to the well drillers and landowners of the area who provided well records and access to their property.

CONCEPT OF THE RIVER AQUIFER AND ACCOUNTING SURFACE

The method required the definition and delineation of the river aquifer and the definition and generation of the accounting surface within the river aquifer. The river aquifer consists of permeable, partly saturated sediments and sedimentary rocks that are hydraulically connected to the Colorado River so that water can move between the river and the aquifer in response to withdrawal of water from the aquifer or differences in water-level elevations between the river and the aquifer. The subsurface limit of the river aquifer is the nearly impermeable bedrock of the bottom and sides of the basins that underlie the Colorado River valley and adjacent tributary valleys, which is a barrier to ground-water flow. The accounting surface represents the elevation and slope of the unconfined static water table in the river aquifer outside the flood plain and the reservoirs of the Colorado River that would exist if the river were the only source of water to the river aquifer. The accounting surface extends outward from the edges of the flood plain or a reservoir to the subsurface boundary of the river aquifer (fig. 3). The water-table elevation in the river aquifer near a well or well field is assumed to be the same as the elevation of static water levels in the wells. This method provides an organized way to identify those wells presumed to yield water that will be replaced by water from the river by determining if the elevation of the static water table at a well is above or below the accounting surface.

Wells that have a static water-level elevation equal to or below the accounting surface are presumed to yield water that will be replaced by water from the river (fig. 3, wells labeled R). Pumping water from a well completed in the river aquifer where the elevation of the static water level in the well is below the elevation of the accounting surface will eventually cause the slope of the hydraulic gradient between the river and the well to be downward toward the well. This, in turn, will result in the movement of water from the river into the river aquifer.

Wells that have a static water-level elevation above the accounting surface are presumed to yield water that will be replaced by water from precipitation and inflow from tributary valleys (fig. 3B, wells labeled T). Water from tributary inflow that recharges the river aquifer creates local ground-water mounds or ridges in the river aquifer that have static water-level elevations above those of nearby reaches of the river or the nearby water table beneath the flood plain. This situation occurs in the southeast end of Mohave Valley (pl. 10) where tributary inflow associated with Sacramento Wash (Owen-Joyce, 1987) has created a ground-water mound. Although tributary inflow is less than 0.1 percent of the annual flow in the river, static water-level elevations in wells near Sacramento Wash are tens to hundreds of feet above the river and the accounting surface (fig. 3B). In an area underlain by a ground-water mound, the static water level in a well can remain above the accounting surface as long as enough tributary water can move to the well to replace water pumped from ground-water storage. If more water is pumped from the well than can be replaced from a tributary source, static water-level elevations in the well will decline below the accounting surface and water will eventually move toward the well from the river. Delineation of the subsurface boundaries of the river aquifer was required prior to the generation of the accounting surface in the river aquifer.

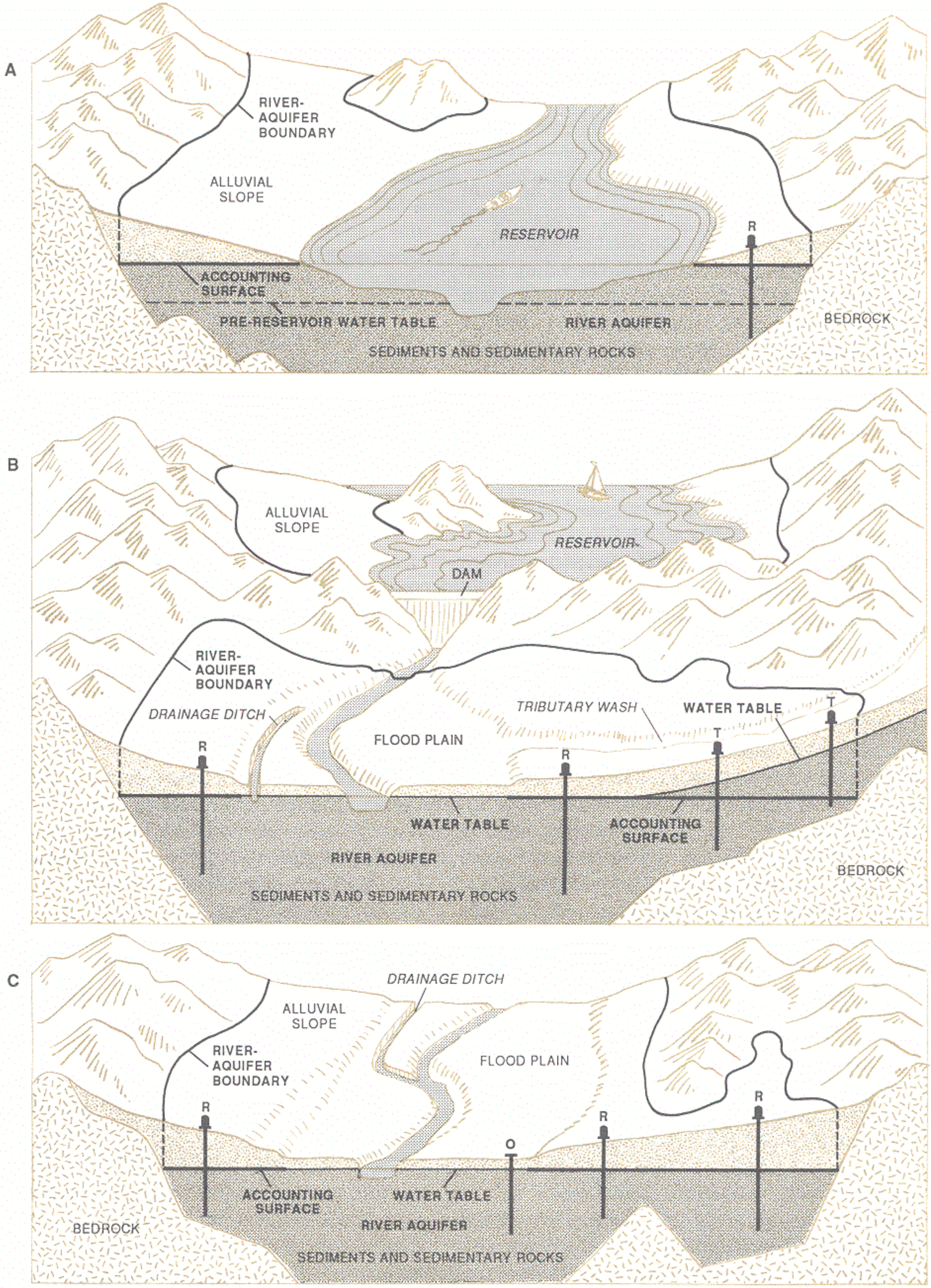


Figure 3. Schematic diagrams showing the river aquifer and accounting surface. Wells labeled "R" have a static water-level elevation equal to or below the accounting surface and are presumed to yield water that will be replaced by water from the river. Wells labeled "T" have a static water-level elevation above the accounting surface and are presumed to yield water that will be replaced by water from precipitation and inflow from tributary valleys. Well labeled "O" is observation well.

DESCRIPTION OF THE RIVER AQUIFER

The river and the underlying and adjacent river aquifer form a complex, hydraulically connected ground-water and surface-water flow system in the lower Colorado River valley from the east end of Lake Mead to Laguna Dam (fig. 1). Water is stored in three surface reservoirs and in the river aquifer. Millions of acre-feet of water are diverted annually from the river channel and reservoirs for irrigation of fields adjacent to the river and for export out of the drainage basin. Much of the irrigation water is transpired by vegetation or evaporates, and the remainder percolates below the root zone into the river aquifer. Water also infiltrates from the river channel, reservoirs, canals, and marshes through the underlying soils and sediments and recharges the river aquifer. Small quantities of runoff that originate from precipitation infiltrate through the beds of washes and intermittent tributary streams and recharge the river aquifer. Ground water flows downgradient through the river aquifer and discharges as seepage into drainage ditches or through the river banks into the river. Water moves back and forth between the surface-water and ground-water systems in response to application of water to irrigated fields and annual changes in water levels in the river. Water is pumped from thousands of wells completed in the river aquifer on the flood plain, on alluvial slopes, and in tributary valleys.

Most of the water in the river aquifer originated from the river because of the hydraulic connection to the river and the overbank flow that occurred prior to building of the dams. Previously unsaturated sediments and sedimentary rocks of the river aquifer adjacent to Lakes Mead, Mohave, and Havasu became saturated with Colorado River water as the reservoirs filled after the dams were closed (fig. 3A). Ratios of hydrogen and oxygen isotopes in ground water from wells in Mohave, Parker, Palo Verde, and Cibola Valleys indicate that most of the water in the river aquifer beneath the flood plain and terrace deposits originated from the river and that, in many places, river water extends from the flood plain for a considerable distance beneath the alluvial slopes (Robertson, 1991). Precipitation and inflow from tributary valleys contribute some water to the river aquifer.

Source of Water in the River Aquifer

The Colorado River is the source for virtually all recharge to the river aquifer in the lower Colorado River valley from Lake Mead to Laguna Dam because about 96 percent of the annual water supply to the river valley is from the river. Surface and subsurface inflows are summed for Lake Mead above Hoover Dam and for that part of the river valley between Hoover Dam and Laguna Dam.

For the part of the valley dominated by Lake Mead, the surface inflow from the Colorado River is the flow at the streamflow-gaging station above Lake Mead, Colorado River near Grand Canyon, which is 267 miles upstream from Hoover Dam and outside the study area. The mean annual surface flow is 12,270,000 acre-feet for 1923-62 prior to the close of Glen Canyon Dam (102 miles upstream from the Colorado River near Grand Canyon gaging station, also outside the study area) and 10,760,000 acre-feet per year for 1965-90 after the close of Glen Canyon Dam (Boner and others, 1991). The mean annual inflow into Lake Mead from the Virgin River as measured at the streamflow-gaging station, Virgin River at Littlefield (fig. 1), is 172,400 acre-feet for 1930-90 (Boner and others, 1991). The unmeasured annual tributary inflows to Lake Mead are about 156,000 acre-feet (Langbein, 1954). Thus, the total annual tributary inflow to Lake Mead is about 328,400 acre-feet, or about 3 percent of the total inflow to Lake Mead.

For the part of the valley between Hoover Dam and Laguna Dam, the surface inflow from the Colorado River is the flow below Lake Mead as measured at the streamflow-gaging station, Colorado River below Hoover Dam (fig. 1). The mean annual flow is about 10,165,000 acre-feet for 1935-90 (Boner and others, 1991). Mean annual surface and subsurface tributary inflow to the river valley between Hoover Dam and

Imperial Dam is about 144,300 acre-feet (Owen-Joyce, 1987), or about 1.4 percent of the total inflow below Lake Mead. Imperial Dam is 293 miles downstream from Hoover Dam and 6 miles upstream from Laguna Dam. Tributary inflow between Imperial and Laguna Dams is negligible. For the entire study area, the total mean annual tributary inflow is about 472,700 acre-feet, or about 4 percent of the total inflow to the lower Colorado River valley.

Geologic Formations and Their Hydrologic Characteristics

The lower Colorado River flows through a series of wide alluvial valleys separated by canyons cut into bedrock. In areas outside the flood plain, alluvial slopes rise to mountain ranges that rim the valleys. Sediments and sedimentary rocks that fill the structural basins and valleys underlie the flood plain and reservoirs and extend beneath the alluvial slopes of the river valley to the bedrock (fig. 3). The river aquifer generally includes, in descending order, the younger alluvium, the older alluviums including the Chemehuevi Formation, the Bouse Formation, and the fanglomerate or the Muddy Creek Formation. The consolidated rocks of the mountains, referred to in this report as bedrock, form the bottom and sides of the basins.

The younger alluvium of Holocene age consists of unconsolidated gravel, sand, silt, and clay deposited on alluvial slopes and flood plains and in stream channels. The younger alluvium was the last unit deposited by the Colorado River as it meandered across the modern flood plain before the dams and diversion structures were built (Metzger and others, 1973). Beneath the flood plain, the younger alluvium is the upper water-bearing unit of the river aquifer and is from 0 to about 180 feet thick; all but the uppermost few feet of the unit is saturated. Outside the flood plains of the Colorado and Bill Williams Rivers, the unit generally is above the water table and is mapped with the older alluviums. The unit is highly permeable and can yield more than 1,000 gallons per minute of water to wells. Many of the irrigated fields in the lower Colorado River valley are on the surface of the younger alluvium, and drainage ditches and canals are cut into it. Direct runoff from occasional intense rainfall infiltrates into this unit in the stream channels of tributaries and provides a small quantity of recharge to the river aquifer.

The older alluviums of Miocene, Pliocene, and Pleistocene ages consist of weakly to moderately consolidated gravel, sand, silt, and clay of local origin that were deposited in alluvial fans that extend from the mountains into the valleys and basins. Local fan gravels commonly are interbedded with the rounded gravels, sand, and silt deposited by the ancestral Colorado River (Longwell, 1963; Bales and Laney, 1992). The older alluviums overlie the Bouse Formation and Muddy Creek Formation and all older rocks. Near Grand Wash (pls. 5-8), younger basalt underlies or is interbedded with the older alluviums and is included with the older alluviums (Bales and Laney, 1992). In places where the Bouse Formation is absent and the underlying fanglomerate of local origin cannot be distinguished from the older alluviums, the fanglomerate is included with the unit. In this study, the Chemehuevi Formation (Lee, 1908; Longwell, 1936) of Pleistocene age is included with the older alluviums. The Chemehuevi Formation consists of silt, sand, and gravel that was deposited by the Colorado River from near Lake Mead to as far south as Chemehuevi Valley and generally is flat lying. Where saturated by Lake Mead or Lake Mohave, the unit is a productive aquifer and can yield large quantities of water to wells. Potential well yields of the older alluviums range from less than 100 to more than 1,000 gallons per minute and depend on the amount of interbedded rounded gravels tapped by the well.

The Bouse Formation of Pliocene age consists of a thin basal limestone and marl overlain by clay, silt, and sand (Metzger, 1968; Buising, 1990). The Bouse Formation is a marine and estuarine formation that was deposited on fanglomerate and bedrock from Yuma to as far north as the east bank of Lake Mohave in T. 23 N., R. 21 W. (G&SR) (pl. 9), in Arizona (Bentley, 1979a). At this location, it interfingers with the gravel beds of the upper unit of the Muddy Creek Formation. The Bouse Formation is present in the subsurface and crops out in Mohave and Chemehuevi Valleys; in Vidal, Chuckwalla, and Smoketree Valleys in California; and in Cactus and La Posa Plains in Arizona. Clays and silts of the lower part of the Bouse Formation are almost impermeable and can confine water in the underlying fanglomerate. Upper sandy layers of the Bouse Formation are moderately permeable and can yield a few hundreds of gallons per minute of water to wells.

The fanglomerate of Miocene and Pliocene ages consists of moderately to firmly cemented continental sandy gravel of local origin that overlies bedrock and underlies the Bouse Formation (Metzger and others, 1973). Where the Bouse Formation is absent and the fanglomerate cannot be reliably differentiated, it is assigned to the older alluviums. In Chemehuevi Valley, late Tertiary sedimentary rocks yield water to wells at Crystal Beach (pl. 10). These rocks and the fanglomerate are included with the older alluviums in this area. In the Chocolate and Laguna Mountains near Laguna Dam, the conglomerate of Chocolate Mountains and the upper member of the Kinter Formation (Olmsted and others, 1973) are included with the fanglomerate (pl. 19). The fanglomerate is recognized from Yuma to as far north as the point where the Bouse Formation interfingers with the Muddy Creek Formation east of Lake Mohave. North of this point, the conglomerate of the Muddy Creek Formation is equivalent to the fanglomerate. The fanglomerate is fine grained and contains gypsum layers and crystals beneath La Posa Plain (pl. 15). The fanglomerate probably will yield a few to a few hundreds of gallons per minute of water to wells where it is composed mainly of sand and gravel.

The Muddy Creek Formation (Longwell, 1928, 1936; Bohannon, 1984) of late Miocene to Pliocene age consists of moderately to firmly cemented continental gravel, sand, silt, clay, gypsum, and halite of local origin that is interbedded with basalt flows. The Hualapai Limestone (Blair and Armstrong, 1979; Bohannon, 1984, p. 9) and the conglomerate, sandstone, and mudstone of the rocks of the Grand Wash trough (Lucchitta, 1966) are equivalent to and included with the Muddy Creek Formation. The unit overlies bedrock and is widely distributed near Lakes Mead and Mohave and in the Moapa and Virgin Valleys (pls. 1-7). The conglomerate is the most widely distributed facies of the Muddy Creek Formation in the Lake Mead area; the formation consists mainly of conglomerate near Lake Mohave. The conglomerate facies probably will yield a few to as much as 100 gallons per minute of water to wells. A mudstone facies that contains gypsum and halite is present in much of the area near Lake Mead. The mudstone facies is nearly impermeable and will not yield significant quantities of water to wells.

The bedrock consists of volcanic and sedimentary rocks of Mesozoic and Tertiary ages and igneous, metamorphic, and sedimentary rocks of Precambrian, Paleozoic, and Mesozoic ages. Bedrock consists of all rocks older than the fanglomerate and Muddy Creek Formation and is equivalent to the bedrock defined by Metzger and others (1973). These rocks are dense, consolidated, and weakly to firmly cemented. The bedrock is nearly impermeable but probably will yield a few gallons per minute of water to wells where it is fractured or weathered. Some of the volcanic flows and sedimentary rocks of Tertiary age will yield a few tens of gallons per minute to wells.

Delineation of the River-Aquifer Boundary

The river-aquifer boundary was delineated primarily on information from previously published geologic, hydrologic, and geophysical studies. Areal extent, saturated thickness below river level, and subsurface continuity of sediments and sedimentary rocks that form the river aquifer were inferred from hydrologic, geologic, and geophysical maps and studies and lithologic, geophysical, and drillers' logs of wells. Extent and thickness of low-density sediments that were assumed to form the river aquifer in several areas were determined by geophysical-gravity studies done during this investigation (see section entitled "Gravity Studies"). The position of the river-aquifer boundary shown on plates 1-19 is intended to be directly above the subsurface intersection of the accounting surface and the bedrock surface (fig. 3). The position is approximate in much of the study area because subsurface data from boreholes or geophysical studies commonly are not available near the edge of the river aquifer. The boundary generally was drawn near the surface contact between the sediments and sedimentary rocks and the bedrock unless subsurface data were available to better define the position. The river-aquifer boundary was delineated on the basis of the following scientific assumptions:

- The younger alluvium, the older alluviums, the sandy part of the Bouse Formation, the fanglomerate, and the Muddy Creek Formation including the rocks of the Grand Wash trough, collectively, are permeable, hydraulically connected, store and transmit significant quantities of water, and form an aquifer.

- Mountain masses and basin rims of bedrock are effective barriers to ground-water flow; interbasin flow through mountain ranges is negligible in relation to the magnitude of recharge from the Colorado River.

- The position of the river-aquifer boundary generally is a few to a few thousands of feet toward the river from the contact between the alluvial slopes and the bedrock because the slopes are underlain by bedrock near the mountains.

- For the purpose of the gravity studies, low-density sediments that fill structural basins between mountains are equivalent to the sediments and sedimentary rocks that form the river aquifer.

- The river aquifer extends from the flood plain to an intersection with bedrock.

- Saturation and hydraulic connection exist in the river aquifer where several hundred feet of sediments and sedimentary rocks are present below river level between the flood plain and the bedrock.

- Static water-level elevations in wells on the alluvial slopes and in adjacent tributary valleys provide local values of the elevation of the water table and indirect evidence of hydraulic connection to the flood plain where sufficient wells are available to define the water table.

The river aquifer is present in five reaches of the lower Colorado River valley from the east end of Lake Mead to Laguna Dam. The reaches are above Davis Dam, Davis Dam to Topock, Topock to Parker Dam, Parker Dam to Draper Lake, and Clear Lake to Laguna Dam. Draper and Clear Lakes are flooded depressions in the flood plain that are connected to the river. The river-aquifer boundary was not delineated between Draper and Clear Lakes because no significant amount of saturated sediments and sedimentary rocks are present outside the flood plain.

Above Davis Dam

After Hoover Dam was closed in 1935, the previously dry sediments and sedimentary rocks above the level of the Colorado, Virgin, and Muddy Rivers became saturated with river water as Lake Mead filled. The maximum water-surface elevation of Lake Mead was 1,225.85 feet in 1983 (Boner and others, 1991). A small quantity of water that originated from the Colorado River is stored in the younger alluvium near the point where the Virgin and Muddy Rivers enter Lake Mead and near the lake shore in Detrital Wash, Las Vegas Wash, and Grand Wash (pl. 5).

Large volumes of the river aquifer are present beneath the lake and adjacent to parts of the shore line around Lake Mead (pls. 1-8). The lake extends for about 105 miles along the Colorado River from Hoover Dam to the Grand Wash Cliffs and about 60 miles up the canyon of the Virgin and Muddy Rivers. Most of the younger alluvium that forms the flood plain of the Colorado River and Virgin River is now submerged beneath the water of Lake Mead. Older alluviums and the underlying conglomerate facies of the Muddy Creek Formation are the main water-bearing units of the river aquifer. Hualapai Limestone caps the Muddy Creek Formation and rocks of the Grand Wash trough and is above lake level in most places. The Hualapai Limestone can be water bearing where it is below lake level in T. 31 N., R. 17 W. (G&SR), at Sandy Point in Arizona (pl. 5).

The Grand Wash trough is a structural basin adjacent to the Grand Wash Cliffs that extends from southwest to northeast across the east end of Lake Mead (pls. 5-8). The trough is partly filled with conglomerate, mudstone, limestone, and basalt flows from below lake level to as much as 2,200 feet above lake level. The river-aquifer boundary was drawn from the lake shore along each side of the trough and across the trough at the location where bedrock appeared to be above lake level.

The Virgin River depression is a deep structural basin that underlies the lower Virgin and Muddy Rivers in the Moapa and Virgin Valleys in Nevada, Arizona, and Utah (Bohannon and others, 1993). The depression is rimmed by the Muddy, Virgin, Beaver Dam, and Mormon Mountains and the Tule Spring Hills (pls. 1-4). Geologic and gravity data (Blank and Kucks, 1989) and seismic and gravity studies (Bohannon and others, 1993) indicate that much of the basin contains at least 3,000 feet of Muddy Creek Formation that is underlain by 0 to as much as 15,000 feet of sedimentary rocks of Tertiary age. A test well (Mobile Virgin 1A) on Mormon Mesa penetrated 2,201 feet of siltstone and 699 feet of gypsum and gypsiferous siltstone of the Muddy Creek Formation. Geologic and geophysical data from the test well provided calibration for the geophysical studies that defined the depression. The river-aquifer boundary was drawn near the rim of the depression on the basis of thickness maps of the Muddy Creek Formation, gravity maps, and geologic maps (Blank and Kucks, 1989; Bohannon and others, 1993). The boundary lines were extended south along each side of the Overton Arm of Lake Mead (pl. 5) on the basis of geohydrologic maps (Bales and Laney, 1992; J.T. Bales and R.L. Laney, written commun., 1993).

Significant volumes of the river aquifer extend beneath and are adjacent to Lake Mohave for about 34 miles from the end of the bedrock canyon below Hoover Dam to the beginning of the bedrock canyon above Davis Dam (pls. 7 and 9). The younger alluvium of the flood plain was covered with river water, and previously dry sediments and sedimentary rocks became saturated to an elevation of 645 feet as the reservoir filled behind Davis Dam. The river-aquifer boundary was drawn near the contact between the bedrock and the sediments and sedimentary rocks around the rim of the basin and around several isolated hills of bedrock.

Davis Dam to Topock

Mohave Valley below Davis Dam is a trough rimmed by the bedrock of the Dead Mountains on the west and the Black Mountains on the east (pls. 9 and 10). The river enters the valley in a bedrock canyon below Davis Dam and exits the valley into a bedrock canyon at Topock. The river aquifer is adjacent to the channel or the flood plain of the Colorado River for about 40 miles from Bullhead City to the end of the valley at Topock. The river flows in a narrow channel cut into the older alluviums for about 10 miles below Davis Dam to Big Bend. Below Big Bend, the flood plain widens and ranges from 2 to 5 miles wide for 30 miles to Topock.

The river aquifer in Mohave Valley consists of the younger alluvium, the older alluviums, the Bouse Formation, and the fanglomerate; the main water-bearing units outside the flood plain are the older alluviums and the fanglomerate. The combined thickness of the units ranges from 0 to more than 5,000 feet in the central part of the valley (Freethey and others, 1986). The younger alluvium was deposited in a trough cut into the older alluviums by the Colorado River at its lowest degradation and ranges from 0 to more than 167 feet thick beneath the flood plain. The beds of many of the larger washes outside the flood plain are underlain by a thin layer of the younger alluvium, which is mapped with the older alluviums. The older alluviums extend from the foot of the bedrock mountain ridges down the slopes to the edge of the flood plain and underlie the younger alluvium beneath the flood plain. The older alluviums are from 0 to more than 600 feet thick near Bullhead City, more than 350 feet thick at the Mohave Power Plant southwest of Laughlin, 350 feet thick near Big Bend, and 200 feet thick near Topock (pls. 9 and 10). The Bouse Formation underlies the older alluviums in much of Mohave Valley and is as much as 254 feet thick. The Bouse Formation is absent in an area near Big Bend where older alluviums overlie fanglomerate (pl. 9). Fanglomerate underlies the Bouse Formation and crops out west of the river near Big Bend and at isolated points around the rim of the valley at the toe of the slope of the mountains. Sacramento Wash enters the southeast end of Mohave Valley where as much as 1,000 feet of the older alluviums, Bouse Formation, and fanglomerate are present in the gap between Mohave and Sacramento Valleys (pl. 10).

The river-aquifer boundary was drawn near the contact between the bedrock and the sediments and sedimentary rocks around the rim of the valley except at Big Bend and Sacramento Wash (pl. 10). The river-aquifer boundary was drawn at the edge of the flood plain at the contact with bedrock along the west side of Big Bend. In the southeastern part of the valley, the boundary was drawn across Sacramento Wash west of a bedrock outcrop near the wash, along the southwest side of the Buck Mountains, across the basin to the Mohave Mountains, and along the Mohave Mountains to Topock.

Topock to Parker Dam

The Colorado River flows in a bedrock canyon below Topock to the upper end of Lake Havasu. The river aquifer is present adjacent to and beneath Lake Havasu for about 30 miles from the end of the bedrock canyon below Topock to the mouth of Bill Williams River (pls. 10 and 12). After Parker Dam was closed, the water in Lake Havasu rose to an elevation of 449.6 feet and saturated as much as 60 feet of previously dry sediments and sedimentary rocks.

The older alluviums, the fanglomerate, and the underlying sedimentary rocks of Tertiary age form the river aquifer at Crystal Beach, in the Lake Havasu City area, and in a valley southeast of Lake Havasu City. Combined thickness of the units is as much as 1,000 feet at Lake Havasu City. The older alluviums and the fanglomerate form the river aquifer in and near the Chemehuevi Indian Reservation west of the lake and north of Chemehuevi Wash. The fanglomerate forms the river aquifer west of the lake and south of Chemehuevi Wash where the contact between the base of the Bouse Formation and the fanglomerate is exposed in a few square miles (pl. 12). At the southeast end of Lake Havasu, sedimentary breccia and sandstone of Miocene age (Sherrod, 1988) are included with the fanglomerate (pl. 12). These units are present beneath the flood plain of the Bill Williams River, crop out along its south bank upstream from Lake Havasu, and extend beneath basalt flows of the Buckskin Mountains.

The river-aquifer boundary generally was drawn near the contact between older alluviums and bedrock. At Crystal Beach and the mouth of the bedrock canyon below Topock, the contact was drawn between sedimentary rocks of Tertiary age and consolidated rocks. The boundary was drawn along the southwest side of the Mohave Mountains to the Bill Williams River, along the north bank of the Bill Williams River near the contact of the fanglomerate and bedrock, across the river at the mouth of a bedrock canyon, and near the edge of the Buckskin Mountains where the fanglomerate pinches out beneath basalt flows. The boundary was drawn near the bedrock contact along the west side of the valley except for two gaps where the bedrock is concealed.

Parker Dam to Draper Lake

Parker, Palo Verde, and Cibola Valleys are parts of a reach of the river that extends about 80 miles from Parker Dam sited in a bedrock canyon to a bedrock canyon downstream from Draper Lake (pls. 11-18). Geohydrologic studies (Metzger and Loeltz, 1973; Metzger and others, 1973; Freethey and others, 1986), drill-hole data, and geophysical data indicate that the flood plain, alluvial slopes outside the flood plain, and several adjacent alluvial valleys are underlain by thick sections of the river aquifer. In much of the reach, the flood plain is from 3 to 9 miles wide and is underlain by younger alluvium to a depth of about 180 feet. Adjacent alluvial slopes and tributary valleys extend from the flood plain more than 46 miles west into California and more than 37 miles southeast into Arizona.

The river-aquifer boundary was drawn from the canyon below Parker Dam, along the bedrock outcrop of the Buckskin Mountains northeast of Parker, around the rim of Cactus Plain to where Bouse Wash enters the plain, and across the north end of the Plomosa Mountains to the La Posa Plain (pls. 12, 13, 15, and 16). At Parker, the fanglomerate yields a few hundreds of gallons per minute of water to wells. Black Peak and Mesquite Mountain are hills of bedrock that are surrounded by the river aquifer. The river aquifer is continuous in the subsurface from La Posa Plain between Mesquite Mountain and Moon Mountain to the flood plain on the basis of a gravity study (see section entitled "Gravity Studies"). Older alluviums cover most of the terraces, alluvial slopes, and floors of adjacent alluvial valleys. In the older alluviums, surface and subsurface layers of rounded gravels deposited by the Colorado River are interbedded with material of local origin; the interbedding indicates that the ancestral Colorado River flowed south from near Parker across Cactus and La Posa Plains to the east of Mesquite Mountain and to the southwest between Mesquite Mountain and Moon Mountain (pls. 12 and 15). Cactus and La Posa Plains east and southeast of Parker in Arizona (pls. 12 and 15) are underlain by as much as 780 feet of the older alluviums, 1,000 feet of the Bouse Formation, and 990 feet of the fanglomerate; 2,360 feet of these rocks were penetrated in a test hole in section 24, T. 7 N., R. 19 W. (G&SR). From Parker to south of Quartzite, Arizona, the Bouse Formation is continuous in the subsurface. At a site in section 34, T. 8 N., R. 19 W. (G&SR), the Bouse Formation is at least 1,000 feet thick and yielded 250 gallons per minute of water to a test well. In T. 7 N., R. 19 W. (G&SR), the Bouse Formation is 520 to 590 feet thick; near Quartzite, the unit is as much as 800 feet thick and consists mainly of silt and clay. At a site in section 10, T. 3 N., R. 19 W. (G&SR), the Bouse Formation is more than 529 feet thick and is described as "mudstone" that consists mainly of sandy, silty clay.

The river-aquifer boundary was drawn along the east and west edges of La Posa Plain to about 3 miles north of Quartzite near the probable location where the subsurface contact between the older alluviums and the Bouse Formation is above the water table (see dotted line on plate 15). The Bouse Formation and the underlying fine-grained fanglomerate form a barrier to the movement of significant quantities of ground water. Drillers' logs of wells near Quartzite indicate that the Bouse Formation yields only a few gallons per minute of water to wells. Beneath La Posa Plain, the fanglomerate probably will not yield significant quantities of water because it is fine grained and contains layers and zones of gypsum.

The river aquifer is present beneath the surface of the alluvial slopes from the flood plain southwest of Parker, west to near Vidal, and southwest to the Riverside Mountains (pl. 12). The river-aquifer boundary was drawn along the axis of buried ridges of bedrock between the Whipple and Riverside Mountains; the position of the axis was determined by a gravity study (see section entitled "Gravity Studies"). The most probable position of the river-aquifer boundary between Vidal and the Riverside Mountains is along the axis of the buried ridge. This position is supported by static water-level elevations at Vidal, which are about 57 to 60 feet above the accounting surface. The boundary was drawn northeast to the bedrock of the Whipple Mountains and then along the southeast edge of those mountains to the canyon below Parker Dam.

The river aquifer is present beneath Palo Verde Mesa from the edge of the flood plain west to the McCoy, Mule, and Palo Verde Mountains (pls. 15 and 18). Hydraulic connection to the flood plain is indicated by static water-level elevations in wells and water-surface elevations in drainage ditches near the edge of the flood plain (Owen-Joyce, 1984, p. 16). The river-aquifer boundary was drawn near the bedrock outcrop of the mountains.

The river aquifer is continuous in the subsurface between Chuckwalla Valley and Palo Verde Mesa through the narrows near Interstate 10 on the basis of a gravity study (see section entitled "Gravity Studies"), a seismic profile, and drillers' logs (Metzger and others, 1973). Static water-level elevations indicate hydraulic connection because the water table slopes toward the Colorado River at about 1.3 feet per mile from the eastern part of Chuckwalla Valley through the narrows to Palo Verde Mesa. The bottom of the basin is below sea level from the east end of the valley to 6 miles northeast of Desert Center (pl. 14). Subsurface continuity of the river aquifer and hydraulic connection from the northwestern part to the eastern part of the valley are inferred from drillers' logs and static water-level elevations. The river-aquifer boundary was drawn near the bedrock outcrop around the rim of the valley (pls. 11, 14, 15, and 17).

The river aquifer extends from the flood plain beneath Milpitas Wash and into Smoketree Valley (pl. 18). More than 2,100 feet of older alluviums, Bouse Formation, and fanglomerate are present near the mouth of the valley on the basis of a gravity study (see section entitled "Gravity Studies"), a seismic profile, and data from an oil test hole (Metzger and others, 1973). The river-aquifer boundary was drawn near the bedrock outcrop around the rim of the valley.

Clear Lake to Laguna Dam

The river aquifer is present in a trough east of the river that extends from Clear Lake in a southeasterly direction through Yuma Proving Ground to the Laguna and Muggins Mountains (pl. 19) on the basis of drillers' logs, outcrop patterns, and estimated depths to bedrock in a gravity study by Oppenheimer and Sumner (1981). Hydraulic connection between the river, including Martinez Lake, and the river aquifer in the trough is inferred from water-level elevations in wells. The river aquifer is separated from the river by bedrock of a part of the Chocolate Mountains (also known locally as Laguna Mountains) from about 1 mile south of Martinez Lake to a gap between the Chocolate Mountains and the Laguna Mountains 2 miles southeast of Yuma Test Station. The river-aquifer boundary was drawn near the contact between the older alluviums and the bedrock in most of the area.

The river-aquifer boundary was drawn across a valley between the bedrock of the Castle Dome and Muggins Mountains near a probable ground-water divide about 17 miles east of the river (see dotted line on plate 19). A particle-size log of a nearby well indicates that sediments and sedimentary rocks are present to a depth of about 700 feet, which is about 130 feet below the accounting surface. The position of the well, which has a reported static water-level elevation of 65 feet above the accounting surface, indicates that the well is near a probable ground-water divide. The river-aquifer boundary was drawn across a 3-mile-wide gap between the Laguna and Muggins Mountains 1 mile north of the edge of the Gila River flood plain (see dotted line on plate 19). The gravity study by Oppenheimer and Sumner (1981) indicates that bedrock probably is within a few hundred feet of the surface.

Gravity Studies

By D. R. Pool

Gravity studies were used to help delineate the extent and thickness of the river aquifer by estimating the thickness of low-density sediments (sediments and sedimentary rocks) in a few areas where the river valley has a surficial connection with a tributary valley (fig. 1). The subsurface configuration of the sides and bottoms of the structural basins that contain the river aquifer and limit ground-water flow is poorly known. The presence of shallow bedrock above river level in these areas of surface connection could limit the extent of the river aquifer because the bedrock would be a barrier to the flow of ground water between the river valley and the tributary valley. The presence of a significant thickness of low-density sediments below the level of the Colorado River would indicate that the river aquifer and therefore the accounting surface should extend into the tributary valley. River-aquifer thickness can be estimated by using gravity methods because gravity values are inversely related to the thickness of low-density sediments and because the river aquifer primarily consists of permeable sediments that are much lower in density than the nearly impermeable bedrock. Gravity values at the greatest thickness of low-density sediments are low relative to gravity values where bedrock is shallow. Tributary valleys of interest include La Posa Plain, Vidal Valley, Rice Valley, Chuckwalla Valley, and Smoketree Valley. The older alluviums, the Bouse Formation, and the fanglomerate crop out at the surface in or near these five tributary valleys; drill-hole data provide evidence of the presence of these low-density sediments in the subsurface. The connection between the tributary valleys and the lower Colorado River valley commonly includes a buried bedrock ridge composed of dense crystalline rock.

Gravity measurements were made at more than 600 stations and added to an existing data base for the area of the lower Colorado River (Mariano and others, 1986). Data were collected in each area of interest with the exception of Chuckwalla Valley where the existing data base was sufficient for analysis. The Global Positioning System (Remondi, 1985) was used to survey the latitude, longitude, and elevation of the new gravity stations. The newly collected gravity data were reduced to complete-Bouguer anomaly values and merged with the existing U.S. Geological Survey gravity data base. The data were adjusted for the effects of terrain and Earth curvature to a distance of 103.6 miles using three different radial zones around each station. Gravitational effects of terrain beyond 6,562 feet and Earth curvature beyond 8.7 miles were calculated using digital-terrain data on 15-second, 1-minute, and 3-minute grids and the program BOUGUER (Godson and Plouff, 1988). Effects of terrain between 148 and 6,562 feet were calculated using 7.5-minute digital-elevation models that were available for most of the area and the program TCINNER (Cogbill, 1990). The effects of local terrain within 148 feet were calculated from field notes and topographic maps using a sloping-wedge technique (Barrows and Fett, 1991).

Patterns of low-gravity values in the areas of interest can be simulated as resulting from a thickness of low-density rocks using theoretical-gravity models, provided that the subsurface geology is not complex. Gravity models of the subsurface geology were constructed for each of the areas of interest, with the exception of Rice Valley, to simulate the thickness and extent of low-density sediments. A two and one-half-dimensional gravity model, SAKI (Webring, 1985), was used to simulate the gravity distribution along profiles in each area. A model for the area of Rice Valley was not necessary because field reconnaissance and geologic maps revealed the presence of bedrock outcrops that eliminated the possibility of a hydraulic connection between the aquifer in Rice Valley and the river aquifer.

Reliable estimates of thickness of low-density sediments from the gravity-model simulations were dependent on information that could be used to calibrate the subsurface-density distribution. Calibration information includes data from wells and subsurface geophysics that define the density or thickness of low-density rocks near the area of interest. Calibration information for gravity models in the study area included several deep wells that penetrate bedrock and some seismic data. Gravity profiles were completed in each of the areas where bedrock control was available to calibrate the density of subsurface geologic units in the area. The calibrations resulted in a consistent set of density values for the low-density sediments that was common to all areas and was used for each simulated gravity profile. Densities of 1.90, 2.10, 1.90, 2.10, 2.00, and 2.30 grams per cubic centimeter were used to simulate unsaturated alluvium, saturated alluvium, unsaturated Bouse Formation, saturated Bouse Formation, unsaturated fanglomerate, and saturated fanglomerate, respectively. Metamorphic and granitic rocks underlying the low-density sediments were assumed to have a density of 2.67 grams per cubic centimeter. Volcanic rocks were simulated using densities of 2.42 or 2.50 grams per cubic centimeter.

La Posa Plain

A gravity study indicates that low-density sediments of the river aquifer are continuous in the subsurface below river level from Parker Valley along the south side of Mesquite Mountain into La Posa Plain and that depth to bedrock below river level exceeds 330 feet (fig. 4 and pl. 15). A strong gravity gradient shown by closely spaced gravity-anomaly contour lines south of Mesquite Mountain indicates a large thickness of low-density sediments in the area south of Mesquite Mountain. The complete-Bouguer gravity anomaly values also indicate an arcuate-shaped buried bedrock ridge extending from the Dome Rock Mountains to near a test hole and an adjacent bedrock low that lies to the northwest. The structures are commensurate with antiformal and synformal structures, respectively, mapped by Scarborough (1985). The gravity signature of the ridge is obscured by a strong regional gravity trend from low values (-50 to -42 milligals) in the Dome Rock Mountains to higher values near Mesquite Mountain (-26 milligals) and the Plomosa Mountains (-40 to -32 milligals).

Two-dimensional gravity models were constructed along profiles across La Posa Plain for purposes of calibrating density values of geologic units and estimating the thickness of low-density sediments between the Dome Rock Mountains and Mesquite Mountain (fig. 5). The distribution of complete-Bouguer gravity anomaly values and the data from two test holes in La Posa Plain indicate a deep structural trough between Mesquite Mountain and the Plomosa Mountains (fig. 4). The calibration profile extended from Mesquite Mountain southeast to the Plomosa Mountains through the two test holes. The elevation of the bedrock surface is more than 1,475 feet below sea level at a test hole in the northwest quarter of section 24, T. 7 S., R. 19 W (G&SR). The gravity distribution along a west-east profile extending from the Colorado River valley to the Plomosa Mountains was simulated to estimate the thickness of low-density sediments at the buried ridge between the Dome Rock Mountains and Mesquite Mountain (fig. 4, *A–A′*). The density distribution of the sediments mentioned above resulted in close agreement between simulated bedrock elevation and the bedrock elevation at the test holes along the calibration profile.

The position of the west-east profile was selected to include a well at the southwest corner of section 28, T. 7 S., R. 19 W. (G&SR), which has a water level above the level of the river. No depth or lithologic information is available for the well, but the water level at the well indicates that the river aquifer is present near the level of the river at the site. A planar-regional gravity trend was removed from the complete-Bouguer gravity values in the area of the profile to create the residual-gravity profile simulated by the model. The planar trend was calculated on the basis of gravity values on bedrock at the north end of the Dome Rock Mountains, at Mesquite Mountain, and at the Plomosa Mountains. The resulting gravity model simulated maximum elevation of the bedrock surface as 30 feet above sea level and about 330 feet below river level where the profile crosses the trace of the buried bedrock ridge about 5,000 feet west of the well. Elevation of the bedrock surface at the well was simulated at more than 500 feet below sea level. The elevation of the bedrock surface probably is lower by several hundreds of feet between the structural high along the profile and Mesquite Mountain. Model results indicate that substantial thicknesses of low-density sediments could be present between the Dome Rock Mountains and Mesquite Mountain but probably are restricted to the area of the synformal structure south of Mesquite Mountain.

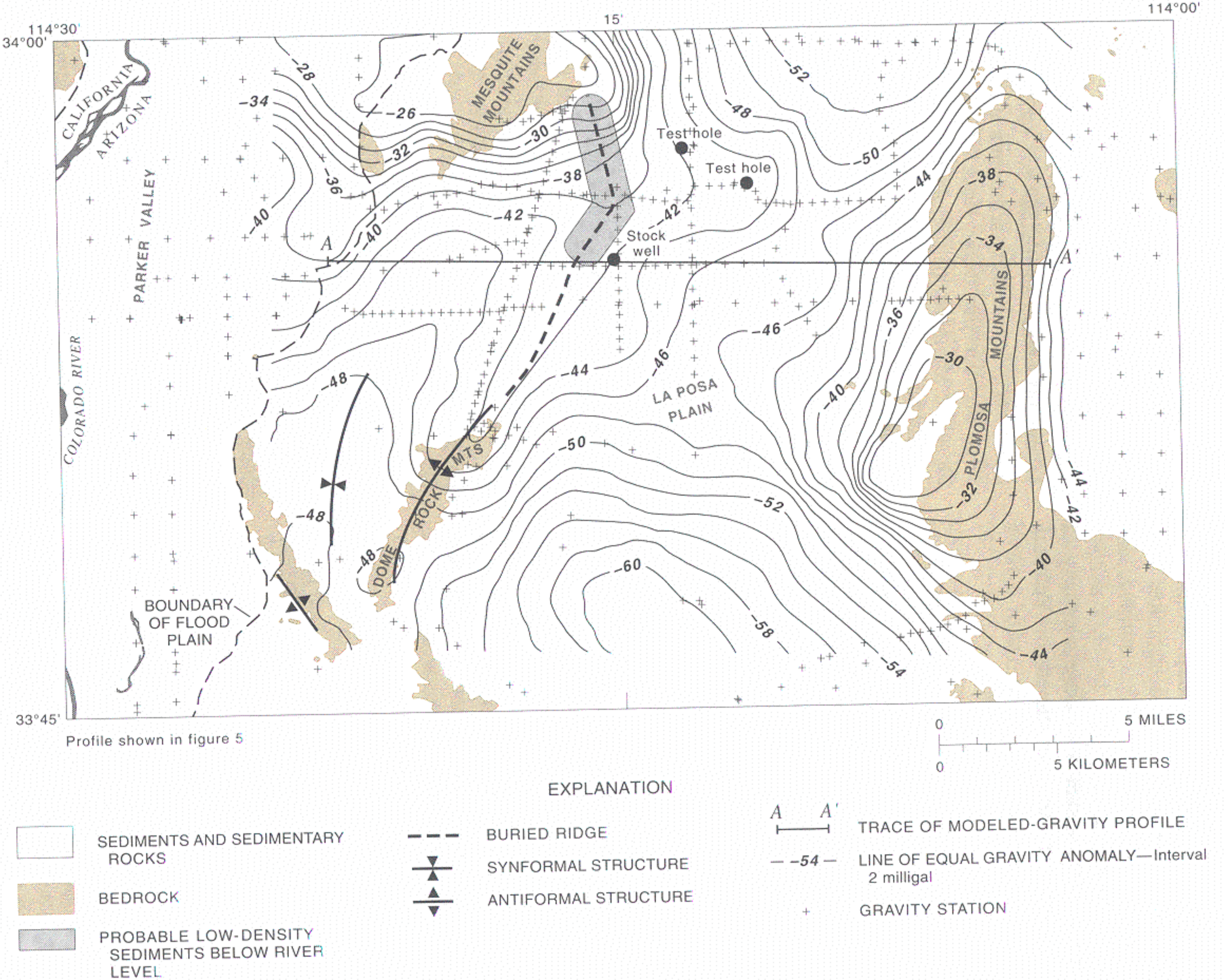


Figure 4. Complete-Bouguer gravity anomaly for La Posa Plain, Arizona (geologic structures from Scarborough, 1985).

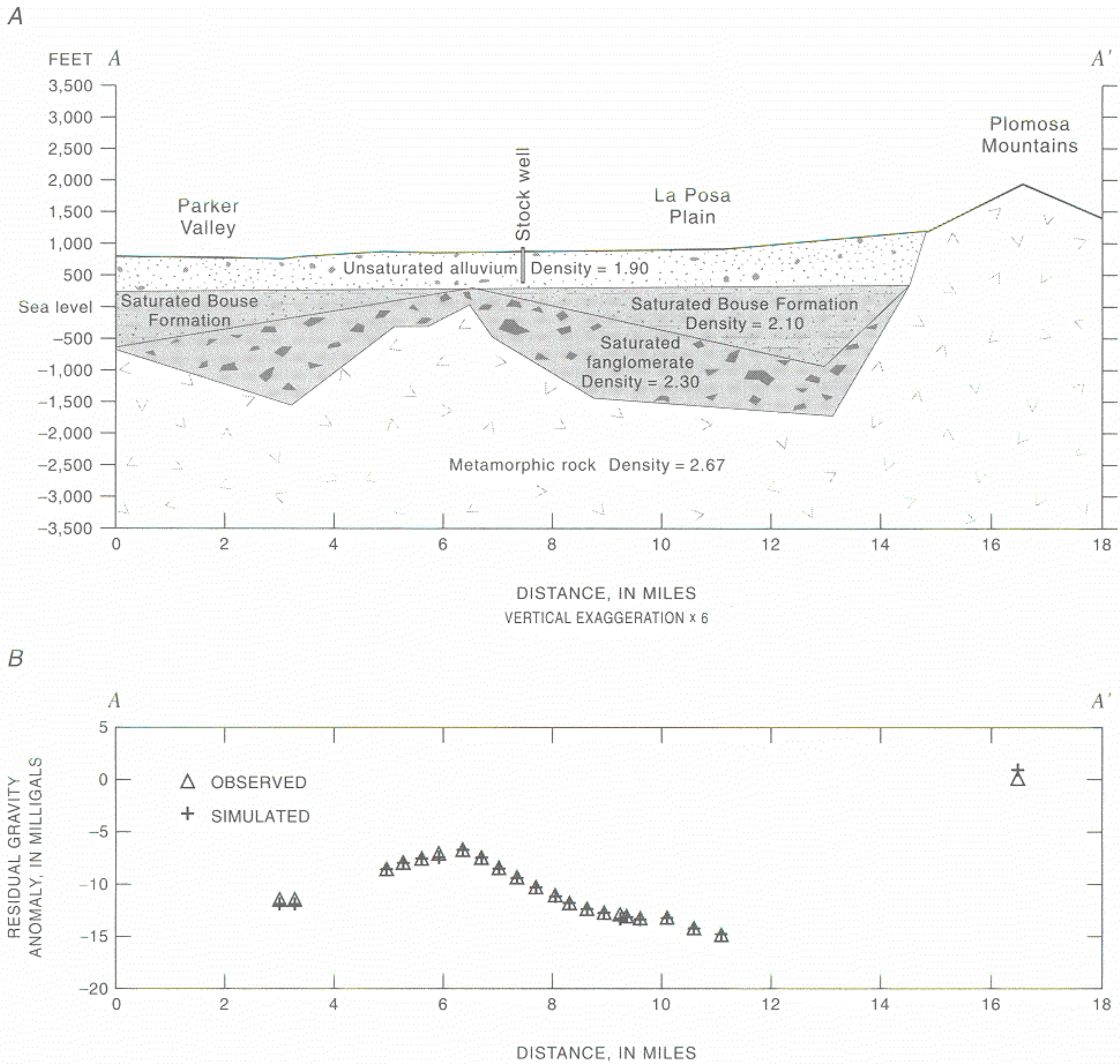


Figure 5. Observed and simulated two-dimensional gravity model for La Posa Plain, Arizona. *A,* Gravity model. *B,* Observed and simulated gravity profile.

Vidal Valley

A gravity study indicates that buried ridges of bedrock are present in the subsurface below river level between the Riverside Mountains and the Whipple Mountains in Vidal Valley (fig. 6). The most probable position of the river-aquifer boundary is along the axis of the buried ridges where the thickness of low-density sediments below river level is minimal. The distribution of complete-Bouguer gravity anomaly values in Vidal Valley reflects the primary structural trends in the crystalline rocks in the area. Northeast-trending antiforms and synforms are crossed by northwest-trending normal-faulted and rotated blocks (Davis

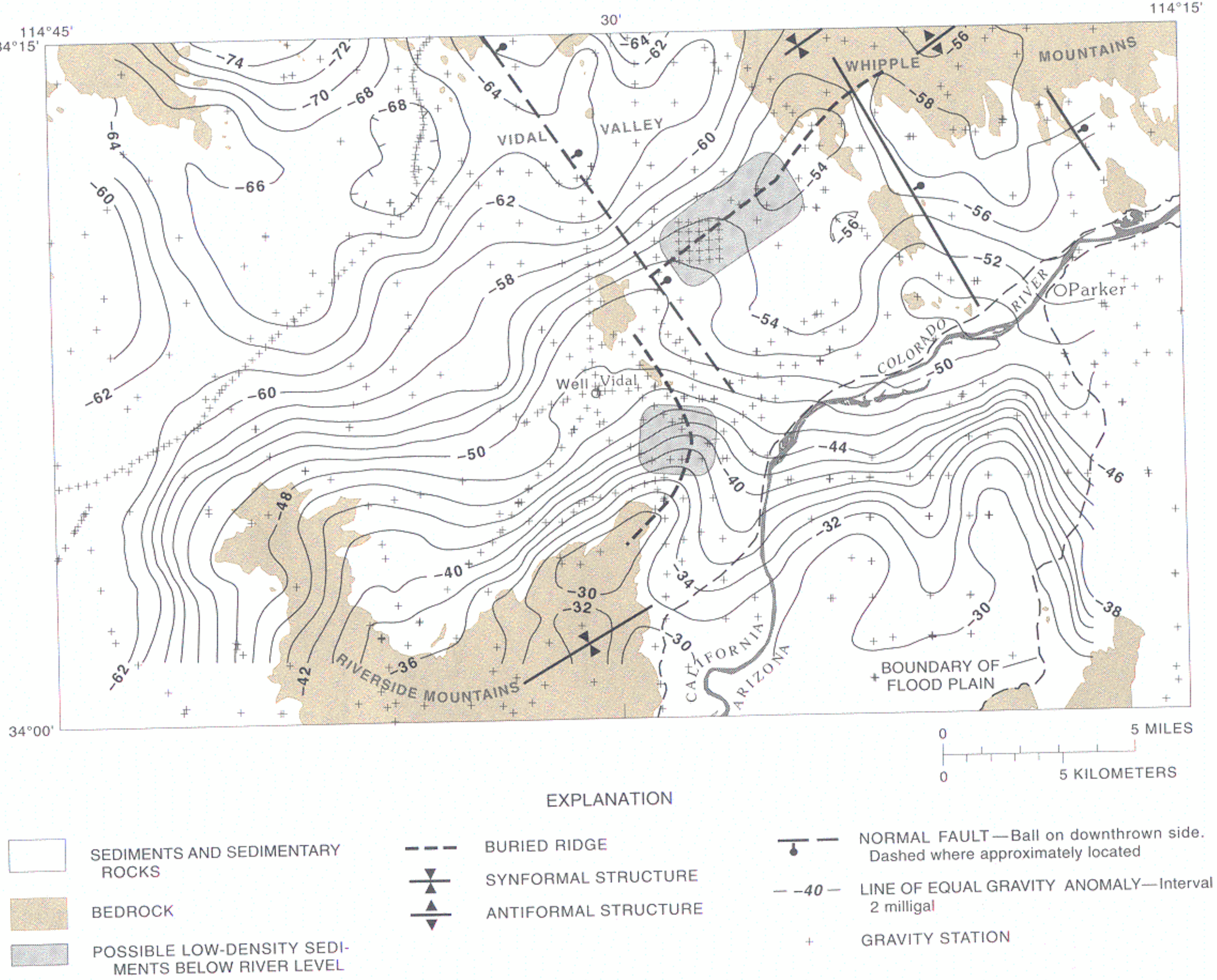


Figure 6. Complete-Bouguer gravity anomaly for Vidal, California (geologic structures from Davis and Anderson, 1991; Carr, 1991).

and Anderson, 1991; Carr, 1991). The normal-faulted blocks are tilted to the southwest resulting in gravity highs at the northeast at the upthrown edge of the block and gravity lows at the southwest at the downthrown edge of the block. A prominent northeast-trending gravity high is present along the southwest projection of an antiformal structure in the Whipple Mountains. An outcrop of volcanic rock on the upthrown side of a prominent normal fault lies at the southwest extent of the gravity high near Vidal, California. The northeast-trending gravity high indicates the presence of a major buried ridge that restricts the thickness of low-density sediments between Vidal Valley and the Colorado River valley. Low-density sediments could be present below river level along the buried ridge in the areas between the two southwest-most normal faults and between the outcrop of volcanic rocks near Vidal and the Riverside Mountains. The area between the two normal faults, however, probably does not have a substantial thickness of low-density sediments below river level because of the lack of a significant gravity low in the area. A two-dimensional gravity model indicated that a substantial thickness of low-density sediments or intermediate-density volcanic rocks of the bedrock could be present below river level between Vidal and the Riverside Mountains; however, subsurface lithologic information is insufficient to determine the rock type.

Chuckwalla Valley

A gravity study indicates that low-density sediments of the river aquifer are continuous from Palo Verde Mesa into Chuckwalla Valley and that depth to bedrock below river level exceeds 560 feet. A two and one-half-dimensional gravity model was completed for the area where Chuckwalla Valley adjoins Palo Verde Mesa using available isostatic-residual gravity anomaly data (fig. 7, *B–B′*). A modeled gravity profile was oriented west to east across an apparent buried bedrock ridge between the McCoy Mountains and Mule Mountains that could restrict the river-aquifer thickness. The modeled gravity profile crossed an area where depth to bedrock had previously been estimated using seismic and gravity data along a north-south profile (Metzger and others, 1973, p. 42). The modeled profile included data from a deep well in the northeast quarter of section 14, T. 7 S., R. 21 E. (SB), that did not penetrate bedrock but represents the minimum thickness of low-density sediments. Seismic data along the seismic-gravity profile of Metzger and others (1973) indicated the presence of a substantial thickness of river aquifer—about 1,250 feet—because the top of bedrock was interpreted to be about 1,000 feet below sea level. Gravity data analyzed in this study indicate that the buried ridge is about 10,000 feet east of the seismic-gravity profile of Metzger and others (1973; fig. 7, this report). The two and one-half-dimensional gravity model (fig. 8) indicates that the river-aquifer thickness is much more restricted at the buried ridge than along the seismic-gravity profile of Metzger and others (1973). The top of the bedrock surface was simulated to be about 330 feet below sea level. The saturated alluvial deposits were simulated as 3 miles wide at the buried ridge; the fanglomerate was simulated as 1.9 miles wide at the buried ridge. The simulated bedrock elevation at the intersection of the gravity profile and the previous seismic-gravity profile was 500-650 feet below sea level, which is similar to the results of the previous investigation by Metzger and others (1973).

Smoketree Valley

A gravity study indicates that low-density sediments of the river aquifer are present in the subsurface below river level in Smoketree Valley and the distribution of complete-Bouguer gravity anomaly values between the Midway Mountains and Palo Verde Mountains indicates that no buried bedrock ridge separates Smoketree Valley from the Colorado River valley (fig. 9). A deep trough that contains low-density sediments and intermediate-density volcanic rocks is present on the basis of the gravity, seismic, and lithologic data from an oil test hole and a deep well. A two-dimensional gravity model was constructed to simulate the thickness of low-density sediments along a north-south profile through the area (fig. 9, *C–C′*; fig. 10). The profile lies along the transect of a previously existing seismic profile (Metzger and others, 1973). Results of the simulation are consistent with data from the oil test hole and

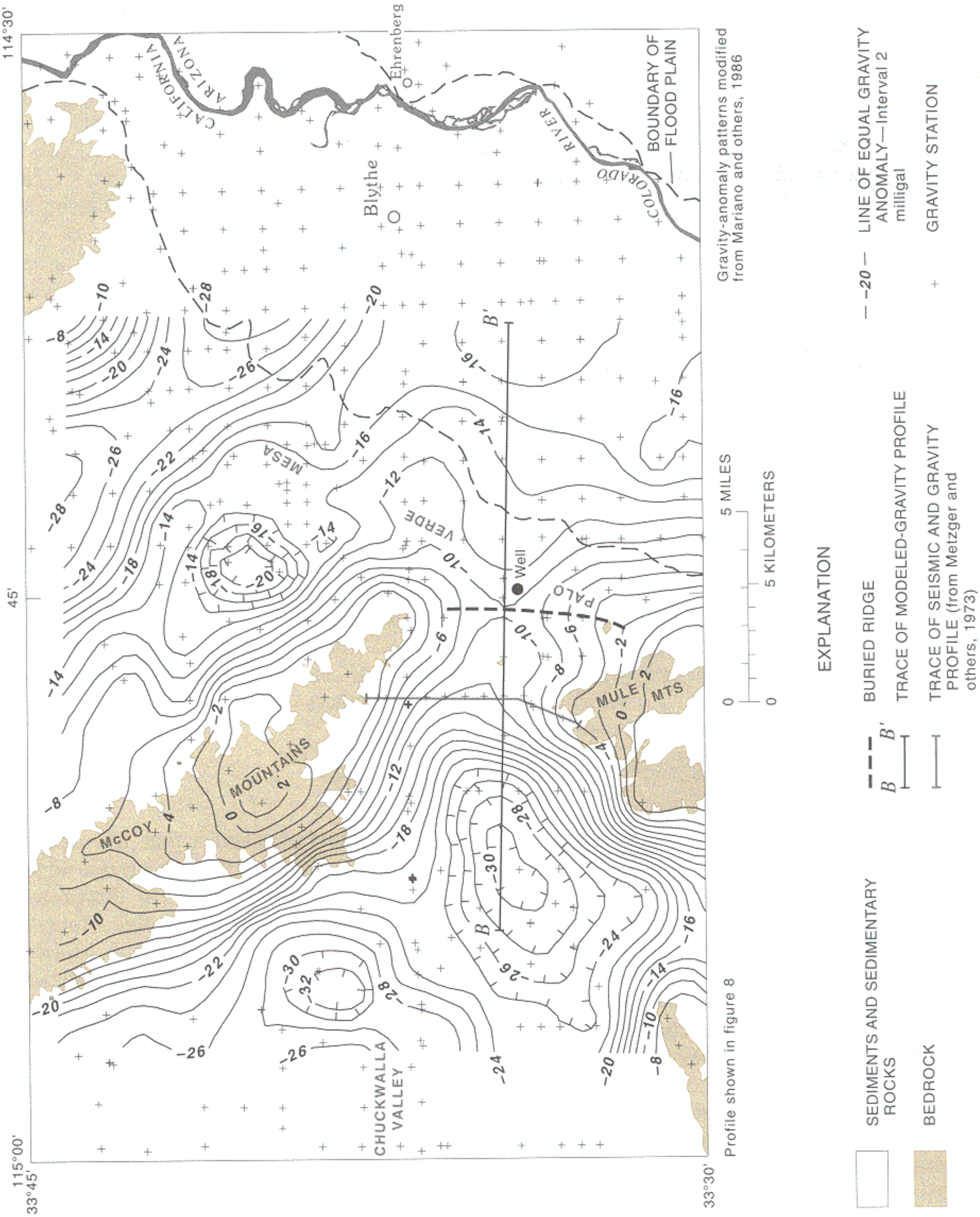


Figure 7. Isostatic-residual gravity anomaly for Chuckwalla Valley, California.

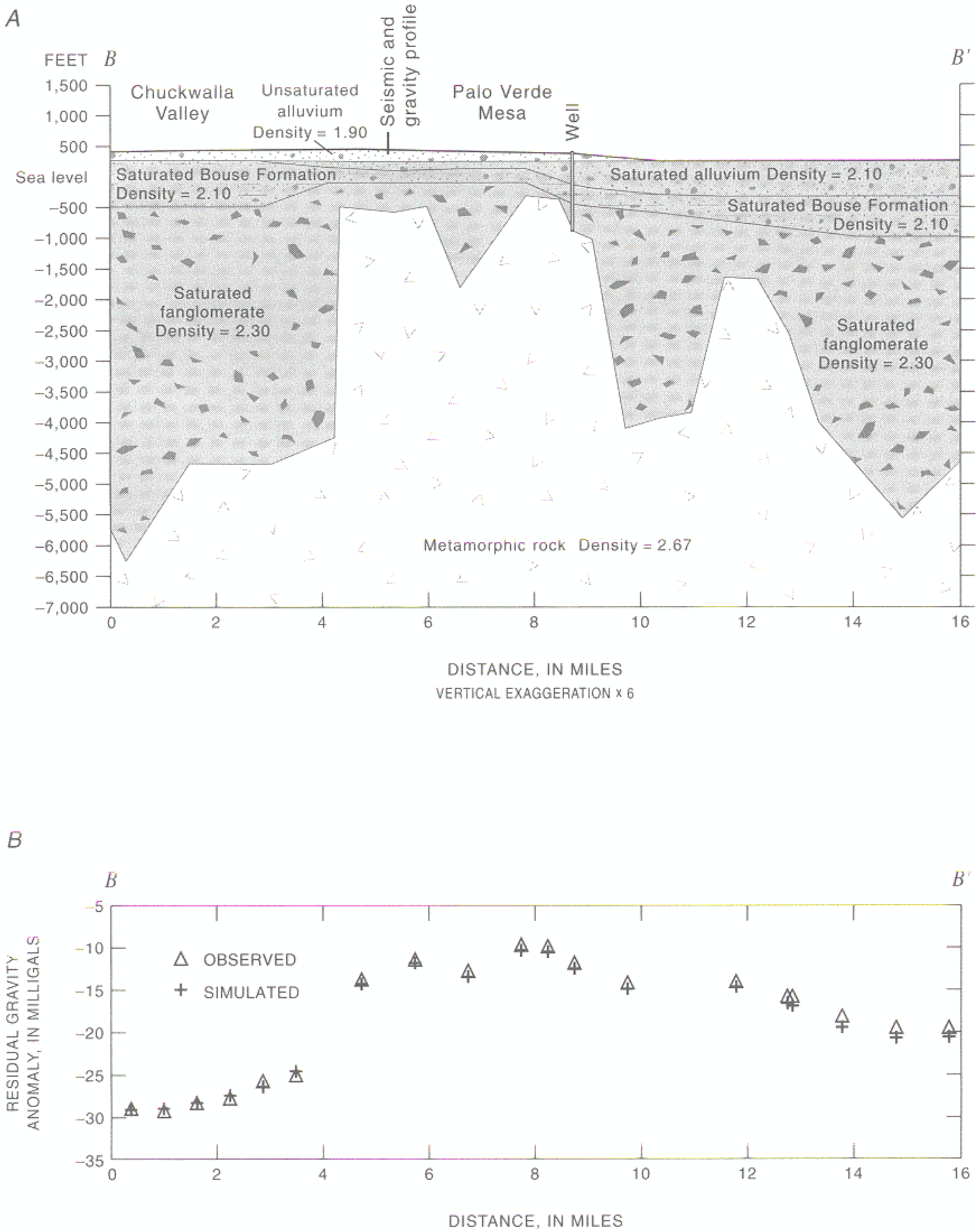
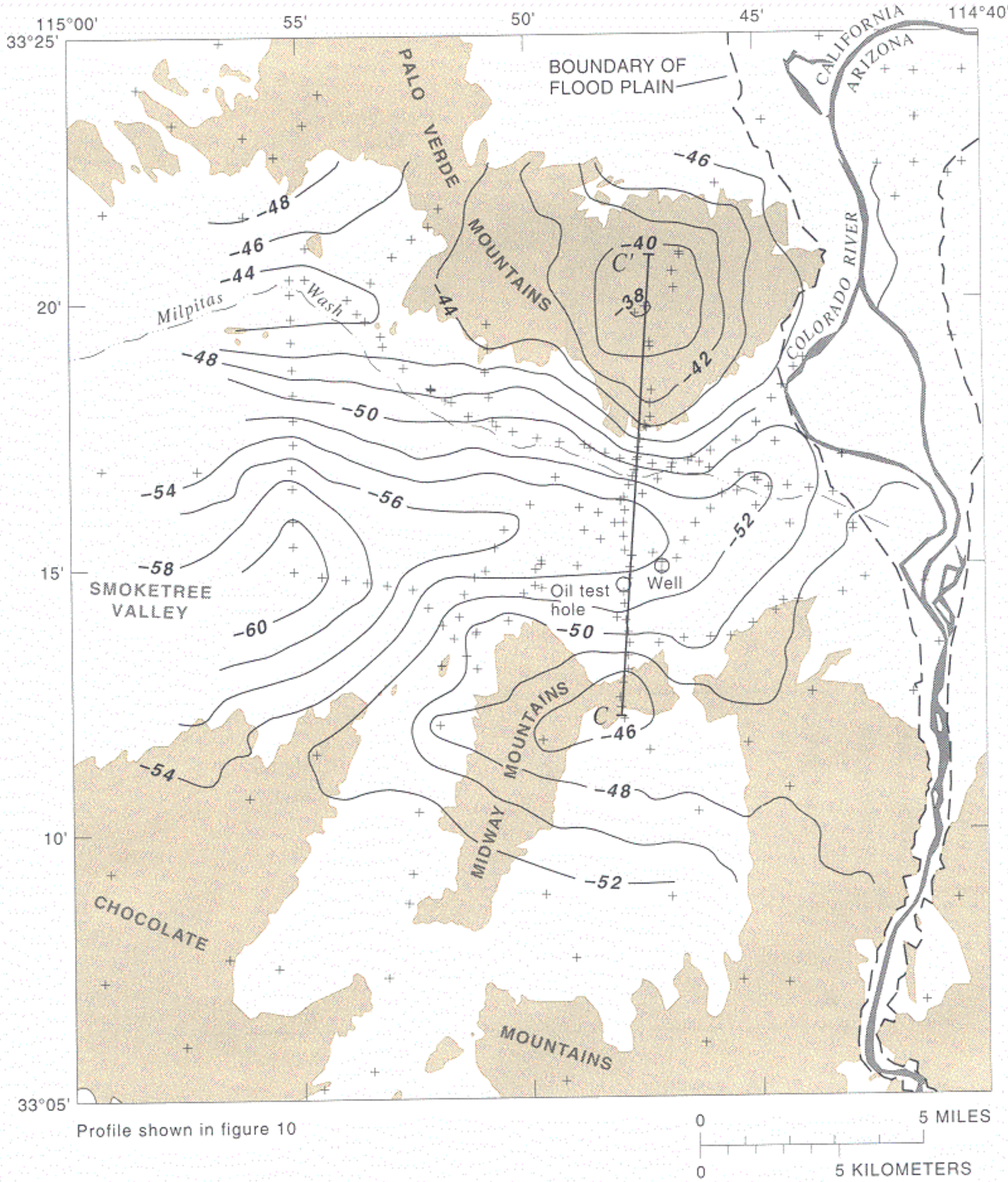


Figure 8. Observed and simulated two and one-half-dimensional gravity model for Chuckwalla Valley, California. *A*, Gravity model. *B*, Observed and simulated gravity profile.



EXPLANATION

(blank box)	SEDIMENTS AND SEDIMENTARY ROCKS
(shaded box)	BEDROCK
C ⊢—⊣ C'	TRACE OF MODELED-GRAVITY PROFILE
— -54 —	LINE OF EQUAL GRAVITY ANOMALY—Interval 2 milligal
+	GRAVITY STATION

Figure 9. Complete-Bouguer gravity anomaly for Smoketree Valley, California.

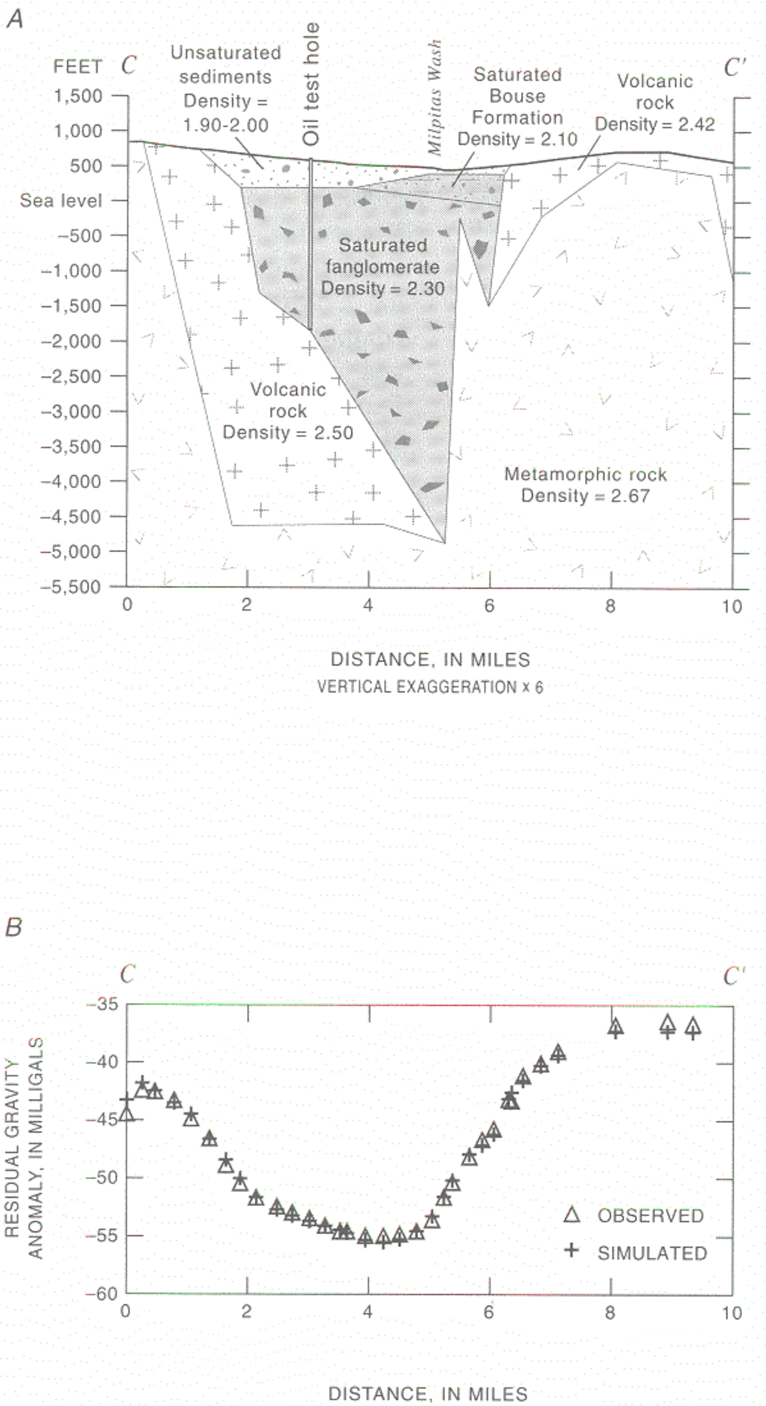


Figure 10. Observed and simulated two-dimensional gravity model for Smoketree Valley, California. *A*, Gravity model. *B*, Observed and simulated gravity profile.

test hole and seismic data. The base of the fanglomerate was simulated to be about 1,540 feet below sea level at the oil test hole. The base of the fanglomerate is at a much lower elevation north of the oil test hole and south of Milpitas Wash. The gravity model and the seismic data indicate that a steeply dipping interface, possibly a normal fault, is present between low-density sediments and high-density rocks near Milpitas Wash.

GENERATION OF THE ACCOUNTING SURFACE

The accounting surface was generated by using profiles of the Colorado River and annual high water-surface elevations of reservoirs, lakes, marshes, and drainage ditches. Where the flood plain is wide and the river is near one side, the geometry of the accounting surface was constructed from the combination of features that have the most influence on the water table near the edge of the flood plain. Static water-level elevations in wells were not used to define the geometry of the accounting surface because static water levels in wells are affected by tributary inflow and most wells do not fully penetrate the river aquifer. The accounting surface was generated without consideration of the time required for water to travel from the river to any point of withdrawal from the river aquifer. The elevation and slope of the accounting surface are shown on the maps by contours that extend from the edge of the flood plain or shore of reservoirs to the river-aquifer boundary (fig. 3). The contours are oriented approximately perpendicular to the general direction of flow of the river and ground water beneath the flood plain. The contours are curved and oriented to indicate interpreted water flow away from or toward the river or flood plain near bends in the river or places where the river enters or leaves areas underlain by the river aquifer (pl. 9).

Water-surface profiles of the river were used to define the elevation and slope of the accounting surface in much of the river valley below Davis Dam. Discharges used to compute the river profiles were determined on the basis of regulated flow conditions of the late 1980's and early 1990's, delivery of full allocations of Colorado River water to users in the United States, and river-channel conditions surveyed between 1980 and 1988. The water-surface profiles were computed for the highest median monthly projected discharge in the Colorado River for 1992–2001. The Bureau of Reclamation determined the discharges with the Colorado River Simulation System and computed the profiles using hydraulic routing and step-backwater methods (Bureau of Reclamation, 1989a, b, 1990; V. LeGrand Neilson, Bureau of Reclamation, written commun., 1991). The discharges used to compute the profiles of the various reaches of the Colorado River for 1992–2001 are as follows:

Reach	Discharge, in cubic feet per second
Davis Dam to Parker Dam	15,511
Parker Dam to Headgate Rock Dam	12,570
Headgate Rock Dam to Palo Verde Dam	10,890
Palo Verde Dam to Imperial Dam	9,646

The water table in the river aquifer surrounding the reservoirs will be at or below the maximum water-surface elevations of the reservoirs unless a significant source of local recharge is available to saturate the river aquifer above that elevation. The accounting surface around reservoirs is flat and its elevation is defined by the annual high water-surface elevation used by the Bureau of Reclamation to operate the reservoirs under normal flow conditions (fig. 3A). The water-surface elevation of Topock Marsh, 455 feet surveyed in 1992, was used to determine the elevation of the accounting surface near the shoreline (pl. 10).

Lakes Mead, Mohave, and Havasu

The accounting surface around Lake Mohave above Davis Dam was delineated using the annual high water-surface elevation of 645 feet; the accounting surface around Lake Havasu above Parker Dam is 449.6 feet (V. LeGrand Neilson, Bureau of Reclamation, written commun., 1991). The annual high water-surface elevation varies at Lake Mead. The water-surface elevation of Lake Mead since 1940 ranged from 1,083.61 to 1,225.85 feet; the maximum water-surface elevation in most years is below 1,205 feet (Boner and others, 1991). Therefore, for the purpose of this report, the accounting surface around Lake Mead was delineated using the elevation of the fixed spillway crest of Hoover Dam, which is 1,205.4 feet.

Davis Dam to Topock

The accounting surface between Davis Dam and Topock was generated from the river profile in the northern and western parts of the Mohave Valley (pl. 9). The water-surface elevation of Topock Marsh was used to define the accounting surface in the southeastern part of the valley. Flow directions in the river aquifer were interpreted to be away from the river at the head of the valley along the west bank and toward the river at Big Bend where the alluvial slope ends against bedrock. Along the east side of the valley, water was interpreted to flow away from the river to the southeast, move parallel to the flood plain toward the south, and return to Topock Marsh and the river above the canyon at Topock (pl. 10). Water moves away from the river for several miles below Big Bend along the west side of the valley, moves parallel to the flood plain, and returns to the river near Topock.

Parker Dam to Draper Lake

Accounting-surface contours were drawn from the mouth of the canyon below Parker Dam 3.1 miles above Headgate Rock Dam (pl. 12) and along both sides of the river and flood plain south to Draper Lake, which is about 12 miles south of Cibola, Arizona (pl. 16). The elevation of the water surface in the river above Headgate Rock Dam is 364.4 feet (V. LeGrand Neilson, Bureau of Reclamation, written commun., 1991). Water is interpreted to flow away from both sides of the pool above the dam to the northwest and to the south.

Water was interpreted to flow to the south beneath and to the east of Parker, and some water returns to the flood plain southwest of Parker. Flow continues in a southerly direction across Cactus Plain to the east of Mesquite Mountain, turns to the southwest, and returns to the flood plain between Mesquite Mountain and Moon Mountain (pl. 15). The elevation and slope of the accounting surface were set to river elevation above Headgate Rock Dam, and water-surface elevations along the drainage ditches on the east side of the flood plain below Parker were adjusted by static water-level elevations in two wells southeast of Parker. From 4 miles above Palo Verde Dam downstream to Draper Lake, the elevation of the accounting surface along the east edge of the flood plain was set to the river profile (pl. 18).

Water was interpreted to flow approximately parallel to the river along the northwest bank below Parker and return to the flood plain along the Riverside Mountains (pl. 12). Water flows parallel to the flood plain between the Riverside and Big Maria Mountains and along the Big Maria Mountains. The elevation of the accounting surface was set to the river profile from Headgate Rock Dam to 0.5 mile below Palo Verde Dam. The accounting surface beneath Palo Verde Mesa from 3 miles below Palo Verde Dam south to the north side of Smoketree Valley is defined by water-surface elevations in the drainage ditches near the west edge of the flood plain (pls. 15 and 18). The measurements of water-surface elevation in the drainage ditches were made by Palo Verde Irrigation District during September and October 1989 when water levels were near the annual maximum elevation. The accounting surface in Chuckwalla Valley is flat and was set to an elevation of 234 feet, which is the representative accounting-surface elevation at the east end of Chuckwalla Valley where it joins Palo Verde Mesa (pl. 15). The accounting surface in Smoketree Valley is flat and was set to the representative elevation at the intersection with the Colorado River flood plain of 212 feet (pl. 18). River profiles were used to define the accounting surface from the north side of Smoketree Valley south to Draper Lake (pl. 18).

Clear Lake to Laguna Dam

The accounting surface was set to the river profile from Clear Lake to 1 mile below Martinez Lake (pls. 18 and 19). In the trough east of the Chocolate Mountains (also known locally as Laguna Mountains), water was interpreted to flow east from the vicinity of Martinez Lake at an elevation of 185 feet, then southeast between the Chocolate and Middle Mountains, and return to the river through the gap below Yuma Proving Ground at an elevation of 150 feet. Water-surface elevations above Laguna Dam vary from 146 to 150 feet. The accounting-surface elevation between Laguna Dam and Imperial Dam was set to 150 feet.

POTENTIAL ADJUSTMENTS TO THE METHOD

The accounting surface was generated on the basis of profiles of the lower Colorado River computed for the highest median monthly projected discharge for 1992–2001, water-surface elevations in drainage ditches that represent regulated flow conditions of the late 1980's and early 1990's, delivery of full allocations of river water to users in the United States, and river-channel conditions surveyed between 1980 and 1988. Major changes in any of these conditions could result in water-surface-elevation changes in the river channel and drainage ditches, which could lead to an adjustment of the accounting surface. Accounting-surface elevations in the river aquifer around Lakes Mohave and Havasu are based on water-surface elevations required to operate the reservoirs under normal flow conditions. A change to either high-discharge or drought-flow conditions could necessitate changes in water-surface elevations required to operate the reservoirs, which could lead to an adjustment in the elevation of the accounting surface.

Future increases in pumping from existing wells or development of new well fields in areas outside the flood plain could cause static water-level elevations in wells that initially were above the accounting surface to decline to or below the elevation of the accounting surface. The lowering of static water levels below the accounting-surface elevation in wells in these areas would result in a change in the designation of the wells from yielding water that will be replaced by tributary water to yielding water that will be replaced by Colorado River water.

Periodic monitoring and evaluation of channel conditions, river discharges, water-surface elevations in drainage ditches, and reservoir operations would provide information needed to determine if an adjustment to the elevations of the accounting surface were warranted. Subsurface conditions in the river aquifer are poorly known near the boundaries of the river aquifer in many areas. Monitoring geologic and geophysical studies and well drilling will provide new information that could allow refinement of the position of the boundaries of the river aquifer.

SUMMARY

Accounting for the use of Colorado River water is required by the U.S. Supreme Court decree, 1964, *Arizona v. California*. Water pumped from wells on the flood plain and from certain wells on alluvial slopes outside the flood plain is presumed to be river water and is accounted for as Colorado River water. A method was developed to identify wells outside the flood plain of the lower Colorado River that yield water that will be replaced by water from the river. The method provides a uniform criterion of identification that is based on hydrologic principles for all users that pump water from wells.

The method is based on the concept of a river aquifer and an accounting surface within the river aquifer. The river aquifer consists of permeable, partly saturated sediments and sedimentary rocks that are hydraulically connected to the Colorado River so that water can move between the river and the aquifer in response to withdrawal of water from the aquifer or differences in water-level elevations between the river and the aquifer. The subsurface limit of the river aquifer is the nearly impermeable bedrock of the bottom and sides of the basins that underlie the Colorado River valley and adjacent tributary valleys. The accounting surface represents the elevation and slope of the unconfined static water table in the river aquifer outside the flood plain and the reservoirs of the Colorado River that would exist if the river were the only source of water to the river aquifer. The accounting surface extends outward from the edge of the flood plain or a reservoir to the subsurface boundary of the river aquifer. This method provides a way to identify those wells presumed to yield water that will be replaced by water from the river by determining if the elevation of the static water table at a well is above or below the accounting surface.

Wells that have a static water-level elevation equal to or below the accounting surface are presumed to yield water that will be replaced by water from the river. Pumping water from a well completed in the river aquifer where the elevation of the static water level in the well is below the elevation of the accounting surface will eventually cause movement of water from the river into the river aquifer. Wells that have a static water-level elevation above the accounting surface are presumed to yield water that will be replaced by water from precipitation and inflow from tributary valleys. If more water is pumped from the well than can be replaced from a tributary source, static water-level elevations in the well will decline below the accounting surface and water will eventually move toward the well from the river.

The flood plain and adjacent alluvial slopes in the lower Colorado River valley and in the tributary valleys are underlain by the river aquifer. The river aquifer includes the younger alluvium, the older alluviums including the Chemehuevi Formation, the Bouse Formation, the fanglomerate, and the Muddy Creek Formation, which overlies nearly impermeable bedrock. The total thickness of the river aquifer ranges from 0 to more than 5,000 feet.

The accounting surface was generated by using profiles of the Colorado River and water-surface elevations of reservoirs, lakes, marshes, and drainage ditches. The river profiles were computed by the Bureau of Reclamation for the highest median monthly projected discharges in the Colorado River for 1992–2001 that were determined by the Colorado River Simulation System. The accounting surface around reservoirs is flat and its elevation is defined by the annual high water-surface elevation used to operate the reservoir under normal flow conditions. The elevation of the accounting surface is 645 feet around Lake Mohave and 449.6 feet around Lake Havasu. The elevation of the accounting surface around Lake Mead is 1,205.4 feet, which is the elevation of the fixed spillway crest of Hoover Dam.

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